PREDICTING RESPIRATORY MOTION FOR ACTIVE CANCELING DURING PERCUTANEOUS NEEDLE INSERTION

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Abstract – **Prediction of bodily motion due to respiration was investigated preparatory to implementation of active compensation for respiration in a robot-assisted system for percutaneous kidney surgery. Data for preliminary testing were recorded from the chest wall of a subject using an optical displacement sensor. The weighted-frequency Fourier linear combiner algorithm, an adaptive modeling algorithm, was used to model and predict respiratory movement. Preliminary results are presented, in which the algorithm is shown to track a 0.86 mm rms respiration signal with 0.11 mm rms error. The general robotic system and compensation scheme are also described.**
***Keywords* - Compensation, adaptive filtering, robot, surgery**

I. INTRODUCTION

The traditional approach to nephrolithotomy and numerous other procedures requiring renal access is open surgery, with its well-known risks and relatively high morbidity and recovery time. Percutaneous approaches were developed as an alternative, allowing morbidity and recovery time to be reduced significantly, and have now become standard. However, percutaneous needle access can be difficult and requires extensive experience due to factors including the lack of three-dimensional information provided to the surgeon by the imaging device. Percutaneous renal access, for example, typically requires needle placement that is accurate to less than 5 mm in order to position the needle in the specified calyx of the kidney [1]. When such procedures are done by hand, error rates are relatively high, and re-puncture is often necessary.

This problem has led to efforts to develop robotic systems to assist in percutaneous needle placement. Potamianos et al. [2] used a stereo pair of two x-ray views registered to a common fiducial system with a five-degree-of-freedom (5-dof) instrumented passive linkage to position a passive needle guide. Bzostek et al. [1] proposed an active robot for similar purposes. Such systems successfully addressed issues of image-to-robot registration and provided convenient means for defining target anatomy, but frequently the radiological profiles of the tools themselves obstructed the view of the kidney. In response to this need, Stoianovici et al. [3] developed the PAKY (Percutaneous Access to the Kidney) radiolucent needle driver. The Mini-RCM (Remote Center of Motion) robot was developed to simplify the orientation of the needle prior to puncture, increase accuracy, and reduce exposure of the surgeon to radiation [4]. The PAKY-RCM combination provides a highly accurate and readjustable percutaneous access platform that is compatible with advanced radiologic imaging devices, keeps the surgeon's hands away from the radiation field, and helps to ensure rapid needle target acquisition, thus minimizing operation time and reducing patient radiation exposure.

One problem that has not been dealt with to date is that of the respiration of the patient, which can cause bodily movement of 1 cm or more in the area of interest, greatly hampering accuracy. Thus far it has been necessary to stop the breathing of the patient so that needle insertion can be performed. Respiration can only be halted for 20-25 seconds at a time [1]. Breaking up the process of needle positioning into such segments makes the operation inefficient and increasing the time needed to complete the procedure, resulting in increased costs. In addition, for the sake of accuracy, when respiration is stopped repeatedly, it is important to ensure that it is always stopped at the same point in the cycle. This is problematic, particularly when the timing of the action is controlled manually by the anesthesiologist [1]. The need to halt respiration also typically means that general anesthesia must be used. If it were possible to achieve accurate needle placement without interrupting respiration, it may also allow the use of regional anesthesia instead of general anesthesia in certain cases, which may decrease patient morbidity [5].

The authors have undertaken to implement active canceling of respiratory motion using the PAKY-RCM system. Adaptive modeling methods will be used to predict the quasi-periodic respiratory motion of the entry point on the skin surface, and of the target point inside the kidney. Immediately before and during needle insertion, the respiratory motion will be predicted and the robot arm will move the needle accordingly, keeping it on target.

Prediction will be accomplished using the weighted-frequency Fourier linear combiner (WFLC), an adaptive algorithm developed specifically for modeling of quasi-periodic signals [6]. The WFLC constructs a dynamic truncated Fourier series model of the disturbance, continually updating its fundamental frequency and harmonic component amplitudes (Fourier coefficients). It is ideal for modeling quasi-periodic biological signals in which neither frequency nor amplitude is fixed. The algorithm has been used in canceling of signals such as hand tremor and heart motion, for applications in microsurgery and rehabilitation [6-8].

The WFLC is an extension of the Fourier linear combiner (FLC) into the realm of variable frequency. The FLC has been

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successfully used to model or cancel fixed-frequency quasi-periodic signals such as evoked potentials [9] and 60-Hz noise in electrocardiograms [10].

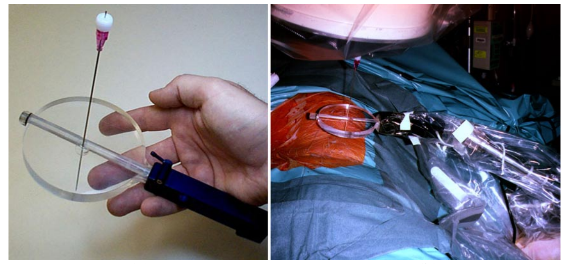
The motion of the target within the body due to respiration as seen in the radiographic images will be recorded preoperatively and registered to the motion of markers on the skin surface, tracked by video camera. Based on the motion of the markers, the robot will dynamically position itself according to the prediction of respiratory motion provided by the WFLC algorithm, in order to keep itself on target. This technique will allow the robotic system to attain accuracy comparable to its present performance, but without requiring the suppression of breathing. The result will be more efficient surgery, less time spent in the operating room, further reduction in exposure of the surgeon and patient to radiation, and possible applicability to a variety of safer and less expensive anesthetic techniques.

II. Robot-assisted surgical system

The robotic percutaneous renal surgery system that will be used to implement active compensation of respiration includes the PAKY needle driver and the mini-RCM robot arm. The radiolucency of PAKY allows unobstructed visualization of the anatomical target and radiological guidance of the needle [3] (see Figure 1). The mini-RCM robot arm implements a fulcrum point located distal to the mechanism [4] (see Figure 2). The arm can precisely orient a surgical instrument while maintaining the position of one point (e.g., needle entry point), making it ideal for percutaneous procedures. A stable base for the robot arm is needed in order to preserve positioning accuracy. For this purpose, the PAKY-RCM combination is mounted on the GREY Arm, shown in Figure 3. This is a passive arm which can be easily manipulated as desired, and then firmly locked in place using a braking mechanism that locks all joints with a single motor [11].

Respiratory motion compensation will require five degrees of freedom: three to compensate entry point displacement, and two to compensate for the rotation of the axis defined by the instantaneous positions of the entry point and target point. The PAKY-RCM-GREY-Arm system will be mounted on a high-precision *XYZ* translation table to provide the necessary degrees of freedom.

Both the internal target point in the kidney and the specified entry point on the skin surface undergo movement due to respiration. The general approach to tracking the respiratory motion will be to record image data over several respiratory cycles for both of these points just before needle insertion begins, and then compute a mapping from the instantaneous entry point location to the instantaneous target point location. Intraoperatively, the system will track only the surface entry point, and will then use the mapping to estimate instantaneous target point position. Entry point tracking will be performed via video tracking of a set of markers on the skin surface near the entry point, and target point tracking via pattern matching techniques applied to C-arm fluoroscope images.



(a) (b)

Figure 1. The PAKY needle driver. (a) Close-up. (b) Used surgically for image-guided percutaneous renal access.

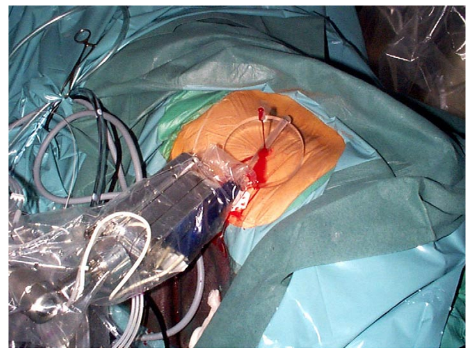


Figure 2. RCM & PAKY performing x-ray guided percutaneous renal access.

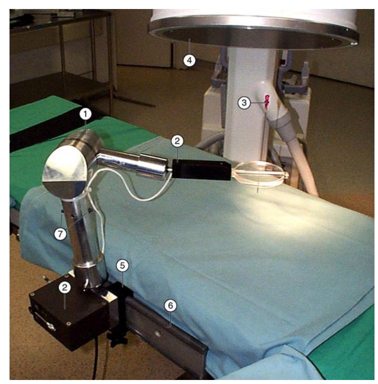


Figure 3. The GREY Arm. (1) GREY Arm. (2) PAKY. (3) Trocar needle. (4) Fluoroscope. (5) Clamp. (6) Rigid custom side rail for mounting.

Using the intraoperative video tracking data, respiratory motion prediction will be performed by the WFLC algorithm so as to minimize needle position error by counteracting delay in tracking and actuation. The translation in 3D of the skin entry point, as tracked via video at 30 Hz, will serve as input to a set of three parallel WFLC algorithm implementations, one for each Cartesian coordinate. At each time step the WFLC will output an estimate of the next position of the entry point, which will serve as the driving command to the *XYZ* table to compensate entry point position. Two additional WFLC implementations are used to predict respiratory displacement for the rotations controlled by the mini-RCM.

The three degrees of freedom of the *XYZ* table are used to compensate the three-dimensional translation of the entry point. The two rotations provided by the RCM robot are then used to rotate the needle so as to keep it aligned with the moving axis defined by the instantaneous position of the chosen entry point on the skin and the instantaneous position of the target point

within the body. This approach preserves the axial control of the needle so that it can be used for puncture in the normal method of PAKY operation. The surgeon retains the smooth control of needle insertion that is needed for successful surgery.

III. Respiratory motion prediction

A. Methods

A preliminary test of respiratory motion prediction using the WFLC was conducted. Displacement due to respiration was recorded from the center of the chest wall of a human subject using a D169 fiber optic displacement sensor Philtec, Inc.; Annapolis, Md.), sampled at 100 Hz. This provided a signal, s_k, which was then used as input to the WFLC algorithm [6]:

$$x_{r_k} = \begin{cases} \sin\left(r\sum_{t=1}^{k} w_{0_t}\right), & 1 \le r \le M \\ \cos\left((r-M)\sum_{t=1}^{k} w_{0_t}\right) & M+1 \le r \le 2M \end{cases} \tag{1}$$

$$\varepsilon_k = s_k - \mathbf{w}_k^T \mathbf{x}_k \tag{2}$$

$$w_{0_{k+1}} = w_{0_k} + 2\mu_0 \varepsilon_k \sum_{r=1}^{M} r\left(w_{r_k} x_{M+r_k} - w_{M+r_k} x_{r_k}\right) \tag{3}$$

$$\mathbf{w}_{k+1} = \mathbf{w}_k + 2\mu \mathbf{x}_k \varepsilon_k \tag{4}$$

where $\mathbf{x}_k = \left[x_{1_k} \quad \cdots \quad x_{2M_k}\right]^T$ is the vector of Fourier harmonic components, w_{0k} is the adaptive weight for fundamental frequency of the model, $\mathbf{w}_k$ is the vector of adaptive amplitude weights or Fourier coefficients, ε_k is the modeling error, M is the order of the model, and μ_0 and μ are the gain parameters governing adaptation of frequency and amplitude, respectively. For these tests, gain parameter values were $\mu_0 = 2 \times 10^{-7}$ and $\mu = 0.05$. Tests were conducted for $M = 1$, $M = 2$, and $M = 3$. The frequency weight, w_{0k}, was initialized at 0.04, all other weights ($\mathbf{w}_k$) were initialized at zero.

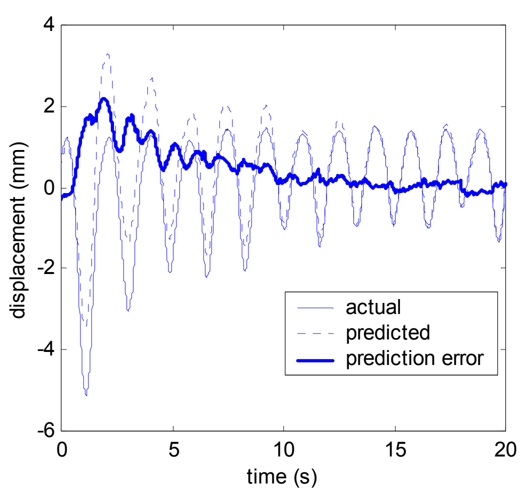


Figure 4. Respiratory motion prediction performance as the WFLC algorithm converges. The thin solid line represents the input signal, the dashed line the prediction by the WFLC, and the thick solid line the prediction error, which can be seen to attenuate with time.

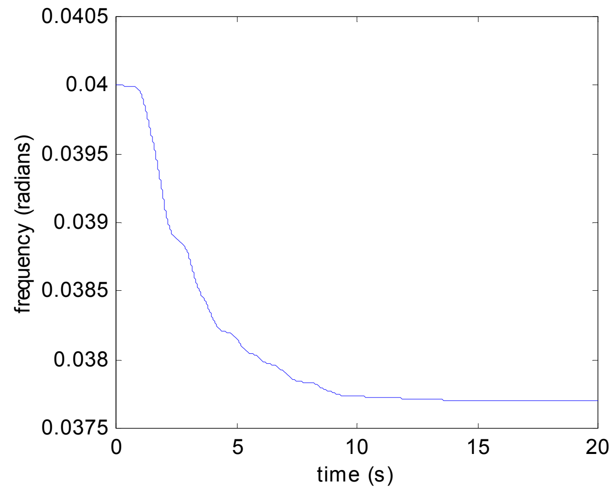


Figure 5. Convergence of the fundamental frequency (w_{0k}) of the WFLC model for the test shown in Fig. 3.

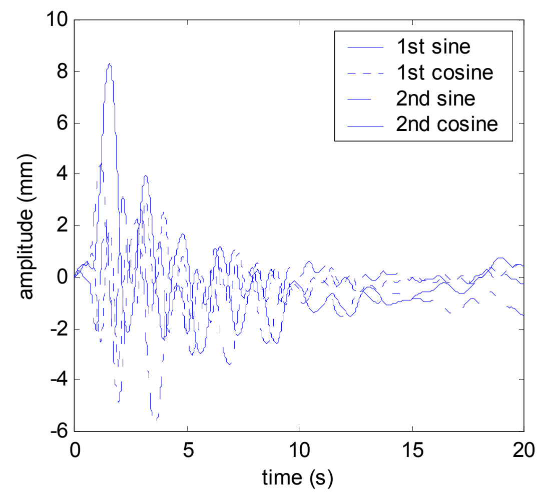


Figure 6. Convergence of adaptive amplitude weights, or Fourier coefficients ($\mathbf{w}_k$), of the WFLC for the test shown in Fig. 3.

B. Results

Figure 4 and Figure 5 display the performance of the filter when two harmonics ($M = 2$) were included in the WFLC Fourier series model. The frequency of the model tracked the signal frequency using what is essentially a nonlinear phase-lock process. As shown in Figure 5, the model frequency was arbitrarily initialized to ω=0.04 (or 0.64 Hz), and can be seen to converge during the first half of the test to the actual respiratory signal frequency of approximately ω =0.0377 (0.6 Hz). The behavior of the filter weights for the amplitudes of the harmonics (i.e., the Fourier coefficients) can be seen in Figure 6. During frequency convergence, the amplitude weights can be seen to oscillate at frequencies proportional to the model frequency error [12]. After the frequency has approximately converged, the amplitude weights "settle down" to track variations in the signal, as seen in the final seconds of Figure 6. In the final 5 s of the example shown in Figure 4, the amplitude of the respiratory

motion itself was 0.856 mm rms, while the prediction error (i.e., the motion that would remain uncompensated by the system) had an amplitude of 0.105 mm rms. As shown in Table 1, this second-order model yields the best results for this particular data set.

Table 1. Comparison of model order (*M*) for data of Figure 4

RMS error during last 5 s of test.

Model order	1	2	3
RMSE (mm)	0.132	0.105	0.110

IV. Discussion

Active compensation of the respiratory motion of the patient will allow the PAKY-RCM robotic percutaneous surgical system to attain a level of needle positioning accuracy comparable to the present state of the art, but without stopping the respiration of the patient. This will allow the surgeon to work continuously on the patient, without the interruptions caused by the need to ventilate the patient.

Prediction of the respiratory motion will allow an active compensation system to accommodate delay in tracking or actuation. In addition, considering the possibility in the future of compensating for more than just respiratory motion (e.g., overall shifts in body position), this prediction guards against erroneous compensatory movements by distinguishing between respiratory motion and any other motion, in which the mapping between entry point and target point motion would not be the same as for respiration.

The preliminary results demonstrate the general feasibility of predicting respiratory motion using the WFLC. The test data suggest initial choices for parameter values; final parameter selection for the application awaits further testing.

The applicability of this technology is not limited to urological procedures. Any percutaneous procedure in which respiratory motion is a factor represents a potential application. Examples include percutaneous biopsies of lesions in the liver and lungs. The technology is also straightforwardly applicable to compensation of heart motion, allowing precise surgery on the freely beating heart. Preliminary studies using the WFLC have already been conducted in this area [8].

V. Conclusion

Prediction of respiratory motion using the weighted-frequency Fourier linear combiner has been demonstrated as a prelude to implementation of active compensation in a system for robot-assisted percutaneous surgery. Preliminary results and a description of the system have been presented.

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